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PROGRAM **facts**

Sequestration

10/2006

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

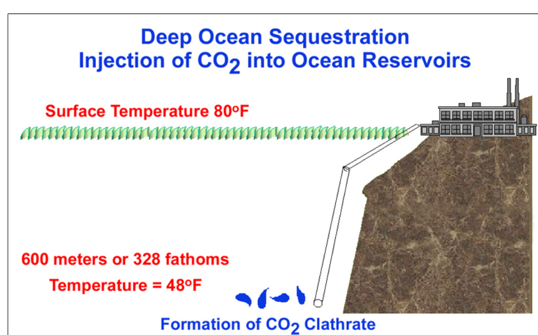
Sequestration of Carbon Dioxide Emissions in the Ocean

Background

The world's oceans represent the largest potential sink for the carbon dioxide (CO_2) produced by human activities (anthropogenic CO_2). Already oceans contain the equivalent of an estimated 140,000 gigatons of CO_2. The ocean's natural carbon transfer processes span of thousands of years and will eventually transfer 80-90 percent of today's man-made CO_2 emissions to the deep ocean. This natural CO_2 transfer may already be adversely affecting marine life near the ocean surface and could also alter deep ocean circulation patterns. The effectiveness of ocean storage techniques depends largely on how long the CO_2 would remain in the deep ocean. Most studies indicate that if CO_2 can be injected into regions of deep oceanic water circulation, it will remain there for approximately 1,000 years. Direct injection of CO_2 into the ocean would reduce both atmospheric CO_2 concentrations and their sharp rate of increase. The purpose of this program is to investigate the technical, economic and environmental feasibility of CO_2 sequestration by injection of liquid CO_2 in the deep ocean.

Description of Program and Future

The purpose of R&D in ocean sequestration is to gain a better understanding of marine ecosystem dynamics at elevated CO_2 concentrations. Ocean sequestration is the injection of liquid CO_2 into the deep oceans for long-term storage. Key concerns about such an approach include the cost of delivering CO_2 500 meters or deeper below the ocean surface, the permanence of injected CO_2, and possible negative effects on the deep ocean ecosystem. The advantage of this approach is the enormous potential storage capacity of the deep oceans. Although this extensive CO_2 storage capacity represents a considerable advantage compared to other CO_2 sequestration technologies, this approach to long-term CO_2 storage is not considered to be a viable option. Cost of transportation and compression of large amounts of CO_2, together with the as yet to be determined impacts on the ocean ecosystems mitigate against a wide application of this CO_2 sequestration technology at this time. Therefore, the DOE will no longer sponsor research and development projects looking at carbon sequestration in the ocean once the existing projects are completed



This figure illustrates the basic concept of Ocean Sequestration. Liquid CO_2 is injected into the Ocean at a depth of 500+ meters. At this depth and temperature, the CO_2 remains as a liquid or a hydrate.

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PARTNERS

Massachusetts Institute of Technology

Monterey Bay Aquarium Research Institute

National Energy Technology Laboratory

University of Massachusetts at Lowell

University of Washington at St. Louis

Projects

Feasibility of Large Scale Ocean Sequestration: Experiments on the Ocean Disposal of CO_2 from Fossil Fuels

Principal Investigator: Dr. Peter Brewer, 831-775-1706 **Partner: Monterey Bay Aquarium Research Institute**

Monterey Bay Aquarium Research Institute will use the Remotely Operated Vehicle (ROV) to carry out pilot experiments involving the deployment of small quantities of liquid CO_2 in the deep ocean for the purposes of investigating the fundamental science underlying concepts of ocean CO_2 sequestration. Below a depth of about 3,000m the density of liquid CO_2 exceeds that of seawater, and the liquid CO_2 is quickly converted into a solid hydrate by reacting with the surrounding water.

Feasibility of Large-Scale Ocean Sequestration: Optimized In Site Raman Spectroscopy on the Sea Floor and Effects of Clathrate Hydrates on Sediment

Principal Investigator: Prof. Jill Pasteris, 316-935-5889 **Partner: University of Washington at St. Louis**

The research group at Washington University in St. Louis will work with MBARI to carry out the first direct in situ analysis on the seafloor of CO_2 clathrate hydrates, their entrained and surrounding fluids, along with sediments adjacent to the clathrate hydrates, using a Raman spectrometer. This information on the physical chemical of clathrate hydrates and clathrate sediment interaction is essential for the evaluation of CO_2 ocean sequestration.

International Collaboration on CO_2 Sequestration

Principal Investigator: Eric Adams, 617-253-6595 **Partner: Massachusetts Institute of Technology**

MIT is conducting a review of recent and ongoing engineering studies concerning techniques for injecting CO_2 into the ocean; a review of experimental studies of the rates of formation and dissolution of CO_2 hydrates; and a review recent and ongoing biological studies concerning organism response to reduced pH and increased CO_2 concentrations.

Laboratory Investigations in Support of Carbon Dioxide-Limestone Sequestration in the Ocean

Principal Investigator: Dr. Dan Golomb, 978-934-2274 **Partner: University of Massachusetts at Lowell, MA**

The University of Massachusetts will establish a data base for the improvement of deep water ocean sequestration using a CO_2-H_2O limestone emulsion. The work will take place over 5 years. The first phase will research the equilibrium characteristics of $CO_2/H_2O/CaCO_3$ emulsions by conducting experiments to quantify the physical characteristics of the liquid and solid phases in emulsion, measure bulk density of emulsion, chemical species concentrations, and the dependence of equilibrium emulsion properties on initial conditions. The second phase will focus on understanding the kinetics of $CaCO_3$ and CO_2 dissolution and reaction. Data collected during this phase will facilitate the development of modeling for future scale up work. Laboratory tests for creating the slurry have been conducted at NETL's Pittsburgh, PA site and at Lowell, MA.

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Accomplishments/Benefits of the Research to Date

In cooperation with U.S. DOE's Office of Science and the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF), the Core R&D effort is funding research to assess the effects of injected CO_2 on aquatic organisms near the injection zone. A large part of the work has been devoted to prerequisite efforts of developing the instrumentation and remotely-operated vehicles needed to conduct experiments in the deep ocean. Experiments have shown that some fish are able to detect and avoid a CO_2 plume. Other experiments have shown that sessile marine organisms contacted by a CO_2 plume experience high mortality rates. Further research efforts are focused on the boundary layer between the CO_2 plume and the surrounding ocean and in measuring the pH gradient from the injection point outward. Other ongoing research is aimed at developing models for the description of impacts of injected CO_2 on the marine biota; a review of experiments on CO_2 hydrate formation and dissolution; and a study of the fate and effects of liquid CO_2 emulsified in calcium carbonate and released in the deep ocean as a "globulsion". This latter approach has the advantage of coating tiny CO_2 droplets with an alkaline coating which prevents immediate acidification of the surrounding water column.

TECHNICAL facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Sequestration

12/2005

System Analyses of CO_2 Capture Technologies Installed on Pulverized Coal Plants

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Background

In the United States, electric power generation is the largest contributor to the buildup of atmospheric carbon dioxide (CO_2). Coal fuels more than half of the power generation and typically produces the cheapest electricity among the fossil fuels. However, relative to CO_2 generation, coal suffers from an inherent disadvantage, since it produces more CO_2 per kWh of electricity than other fuels. The fact that many coal power plants are old and inefficient adds to the problem. Electricity consumption is expected to grow (see Figure 1); and because it is our most abundant fossil fuel, coal will continue to be the dominant fuel. Therefore, coal-based power generation can be expected to provide an even greater CO_2 contribution in the future. As concern mounts over the role that CO_2 and other greenhouse gases play in global climate change, technology and policy options are being investigated to mitigate CO_2 discharge from coal-fired power plants.

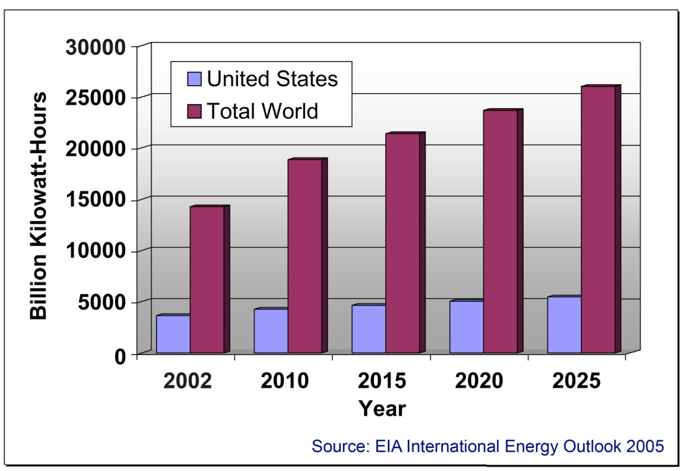

Figure 1. World Electricity Consumption

Current research and development efforts are largely focused toward carbon capture and sequestration, and processes for capturing CO_2 for subsequent storage are rapidly emerging. Each of these options carries with it costs that plant operators, and ultimately consumers, must bear. Thus, economic factors will be a major consideration when deciding which technologies have the potential to be deployed commercially and, hence, justify receiving federal funding for continued development.

R&D personnel are investigating a wide range of CO_2 capture options. Systems analyses and economic modeling of these new and emerging processes are crucial to providing sound guidance to this effort. Ongoing systems analyses are being performed on NETL in-house R&D CO_2 capture technologies, as well as for processes being developed by universities and industry. Some of these studies, particularly on developed technologies, are performed by engineering firms and provide detailed, high quality estimates. Other studies on emerging technologies are of lower quality, because less information is available. Nevertheless, these studies are very valuable for helping to guide R&D activities.

NETL has developed an economic model that enables evaluation of costs for various CO_2 capture, pipeline transport, and geologic storage technologies. The completion of additional studies allows the technical and economic merit of new technologies to be directly compared to a variety of other options. As R&D advances are made and new data emerges, the model is updated to incorporate this information, thus keeping the results generated by the model as current as possible. Therefore, this document is updated annually to reflect these advancements. Similar fact sheets are also developed for gasification and advanced combustion CO_2 capture concepts (circulating fluidized beds and chemical looping).

Project Objective

System analyses have multiple goals: (1) put emerging technologies being developed at the laboratory/bench scale into a systems context (i.e. commercial scale power plant), (2) to screen out unpromising projects before significant resources are spent on them, and (3) to provide guidance to NETL technology managers and researchers working on more promising projects, so that they can concentrate on the aspects of the process that will contribute most to its success.

Cases

Various cases have already been evaluated or are in the process of being evaluated. Results from some of these studies are discussed below. All cases are evaluated assuming 400 MW net power generation, 80% capacity factor, Illinois #6 bituminous coal, 90% CO_2 is captured, compressed to 2,200 psia, transported 10 miles, and stored in a saline formation.

Case	Description
1	Conventional amine scrubbing
2	Advanced amine scrubbing
3	Amine-based solid sorbent
4	Aqueous ammonia, CO_2 capture
5	Aqueous ammonia, multi-pollutant capture
6	PC oxy-fuel combustion, cryogenic ASU
7	PC oxy-fuel combustion, oxygen-selective membrane ASU
8	Case 7 with co-sequestration of CO_2/NOx/SOx

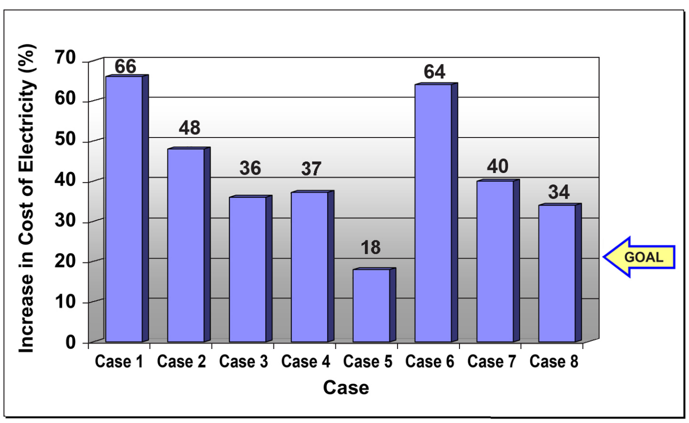

Figure 2. Percent Increase in Cost of Electricity

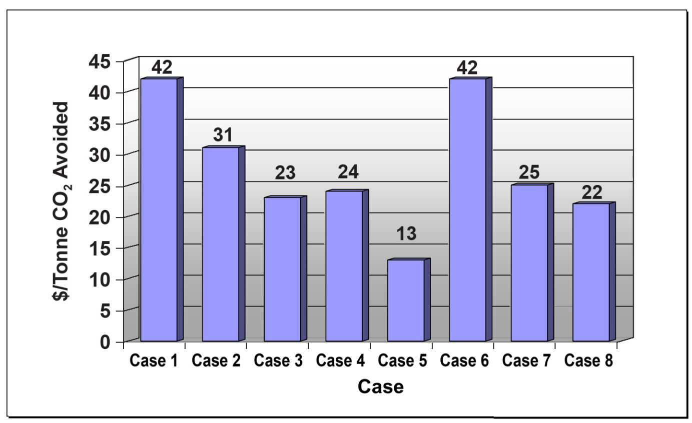

Figure 3. CO_2 Avoidance Cost

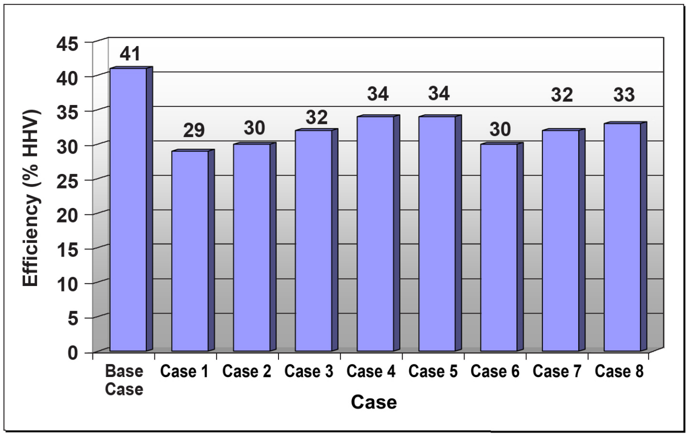

Figure 4. Efficiencies

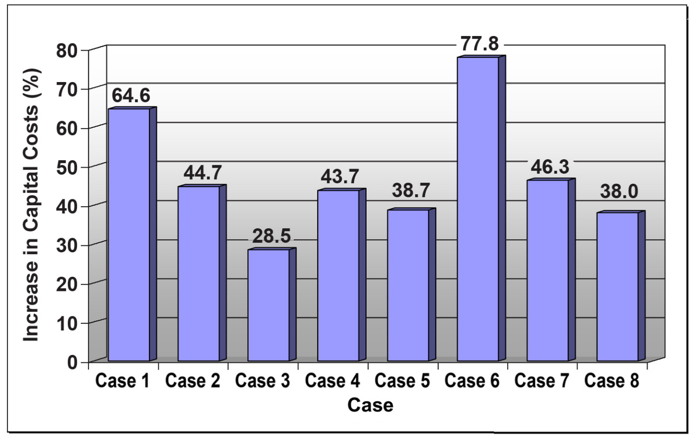

Figure 5. Percent Increase in Capital Costs

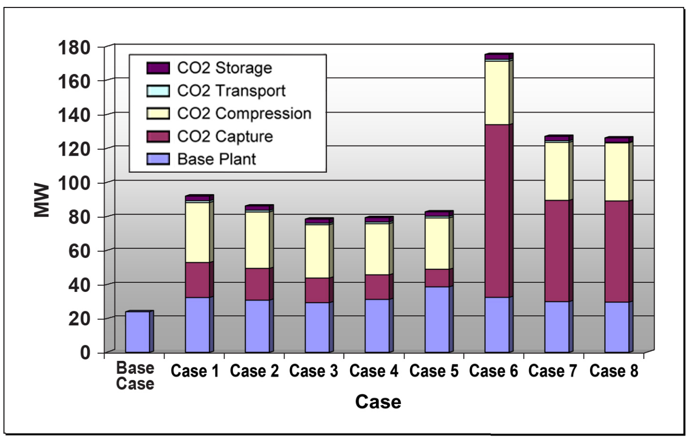

Figure 6. Auxiliary Power Loads

Base Case – This is the case to which most other cases are compared and is based on a design (*Case 7C*) presented in a 2000 DOE/EPRI study [1]. The plant design approach is market-based, and the configuration reflects current information and design preferences—use of a new generation steam turbine and the relative flexibility of a greenfield site. The coal-fired boiler uses staged combustion for low NO_x formation and is also equipped with an SCR unit. A wet limestone forced oxidation FGD is used to limit SO_2 emissions. A once-through steam generator is used to power a double-reheat supercritical steam turbine (3,500 psig/1050°F/1050°F) with a gross power output of 424 MWe [1].

Case 1 – Design basis the same as the Base Case except that an absorber-stripper system, using a 30% aqueous solution of inhibited monoethanolamine (MEA), is added to capture 90% of the CO_2 in the flue gas (~10,374 ton/day). Low-pressure steam (75 Psia/350°F) is used to strip the CO_2 from the MEA at use rate of 1,820 Btu per lb CO_2 captured. Gross power output for this case is 492 MWe [1].

Case 2 – Design the same as Case 1 except that an advanced amine scrubber, based on Fluor Daniels Econamine FG Plus^{SM} Technology, is used to capture CO_2. Advantages realized through the use of this solvent are:

- Improved solvent formulation results in increased reaction rates and higher solvent capacity.
- Split flow configuration uses less stripping steam.
- Stripping with condensate flash stream decreases solvent circulation rate and requires less stripping steam.
- Absorber intercooling increases solvent capacity, decreases absorber size, and decreases capital cost.
- Integrated steam generation decreases stripping steam.

A net regeneration steam rate of 1,200 Btu per lb CO_2 captured was assumed. Gross power output for this case is 486 MWe [2].

Case 3 – Design utilizes an Amine-enhanced solid sorbent in a radial-flow, fixed bed absorber design for post-combustion CO_2 capture. The solid-sorbent (being developed at NETL) utilizes the same amine chemistry as the MEA wet-scrubbing system except that amine groups are attached to a solid substrate. This has the advantages of: (1) a reduced steam load and (2), a reduced parasitic electric load. The steam load is expected to be near 780 Btu of low pressure steam per lb CO_2 captured compared to 1,820 Btu for MEA. The parasitic electric load is reduced because there is no solvent to circulate. Gross power output for this case is 478 MWe [7, 8].

Case 4 – NETL conceptual design for an Aqueous Ammonia CO_2 capture process. This technology is being developed at NETL in co-operation with PowerSpan Corporation. Based on NETL R&D lab results, the following four advantages of the aqueous ammonia process compared to conventional amines have been identified and used in a recent NETL systems analysis: (1) reduced steam load (500 Btu per lb of CO_2 captured), (2) more concentrated CO_2 carrier, (3) lower chemical cost, and (4) multi-pollutant control with salable by-products. Case 4 is for CO_2 capture only; however, an additional advantage of the AA technology is the opportunity for multi-pollutant control where SO_2 and NOx are removed as saleable by-products (ammonium nitrate and ammonium sulfate). Powerspan Corporation recently conducted a commercial-scale demonstration of an AA-based multi-pollutant control technology called "ECO™" for scrubbing SO_2, NOx, and mercury from flue gas [3, 4].

Case 5 – Design same as Case 4, except that the PowerSpan multi-pollutant control technology is used for CO_2, SO_2, and NO_x capture with a by-product credit taken for the sale of ammonium nitrate and ammonium sulfate. Gross power output for this plant is 482 MWe [3].

Case 6 – A supercritical steam plant employing a cryogenic air separation unit to provide oxygen at 95% purity to the boiler (oxy-fuel combustion). The treated flue gas (approximately 80% CO_2, 17% N_2, and 3% O_2) passes through a condenser that separates H_2O from the CO_2. Gross power output is 575 MWe [5, 6, 9].

Case 7 – A similar configuration as Case 6 except for the use of an oxygen-selective ion transport membrane, instead of a cryogenic air separation unit, to provide oxygen. A 44% decrease in ASU capital cost and 37% decrease in ASU parasitic loads are assumed in this case. Gross power output for this case is 527 MWe.

Case 8 – Design basis same as Case 7 except co-sequestration of CO_2/NOx/SOx is carried out. Based on a 2004 IEA GHG report, "there are no technical barriers with co-sequestration of these components". Thus, this case assumes no SCR, no FGD and no increase in compression or transmission capital costs. A more rigorous analysis to verify Cases 6, 7 and 8 is currently being performed by NETL/Parsons/Air Liquide and Babcock & Wilcox. Gross power output is 527 MWe [9].

References

1. *Evaluation of Innovative Fossil Fuel Power Plants with CO_2 Removal*, EPRI, Palo Alto, CA, U.S. Department of Energy – Office of Fossil Energy, Germantown, MD, and U.S. Department of Energy/NETL, Pittsburgh, PA: 2000.1000316.
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TECHNICAL

facts

U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

4/2006

SYSTEM ANALYSES OF CO_2 CAPTURE TECHNOLOGIES INSTALLED ON INTEGRATED GASIFICATION COMBINED CYCLE PLANTS

Background

In the United States, electric power generation is the largest contributor to the buildup of atmospheric carbon dioxide (CO_2). Coal fuels more than half of the power generation and typically produces the cheapest electricity among the fossil fuels. However, relative to CO_2 generation, coal suffers from an inherent disadvantage, since it produces more CO_2 per kWh of electricity than other fuels. The fact that many coal power plants are old and inefficient adds to the problem. Electricity consumption is expected to grow (see Figure 1); and because it is our most abundant fossil fuel, coal will continue to be the dominant energy source. Therefore, coal-based power generation can be expected to provide an even greater CO_2 contribution in the future. Due to the potential for CO_2 to contribute to global climate change, technology and policy options are being investigated to mitigate CO_2 emissions from coal-based power plants.

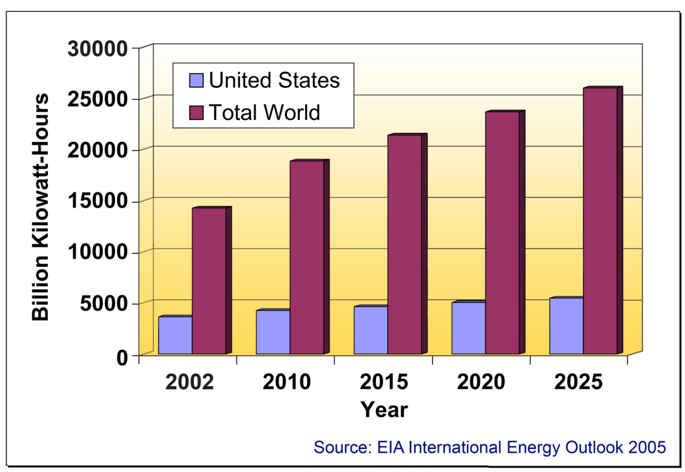

Figure 1. World Electricity Consumption

Current research and development (R&D) efforts are largely focused toward implementation of Integrated Gasification Combined Cycle (IGCC) power generation in conjunction with carbon capture and sequestration. Technologies related to capturing CO_2 from IGCC plants for subsequent storage are rapidly emerging. Each of these options carries with it costs that plant operators, and ultimately consumers, must bear. Thus, economic factors will be a major consideration when deciding which technologies have the potential to be deployed commercially and, hence, justify receiving federal funding for continued development.

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R&D personnel are investigating a wide range of CO_2 capture options. Systems analyses and economic modeling of these new and emerging processes are crucial to providing sound guidance to this effort. Ongoing systems analyses are being performed on NETL in-house R&D CO_2 capture technologies, as well as for processes being developed by universities and industry. Some of these studies, particularly on developed technologies, are performed by engineering firms and provide detailed, high quality estimates. Other studies on emerging technologies are of lesser detail, due to limited availability of supporting information. Nevertheless, these studies are very valuable for helping to guide R&D activities.

NETL has developed an economic model that enables evaluation of "Nth plant" costs for various CO_2 capture, pipeline transport, and geologic storage technologies. The completion of additional studies allows the technical and economic merit of new technologies to be directly compared to a variety of other options. As R&D advances are made and new data emerges, the model is updated to incorporate this information, thus keeping the results generated by the model as current as possible; and this document is updated annually to reflect these advancements. Similar fact sheets are also available for pulverized coal and advanced combustion CO_2 capture concepts.

Project Objective

Systems analyses have multiple goals: (1) to put emerging technologies being developed at the laboratory/bench scale into a systems context (i.e., commercial scale power plant), (2) to screen out unpromising projects before significant resources are spent on them, and (3) to provide guidance to NETL technology managers and researchers working on more promising projects, so that they can concentrate on the aspects of the process that will contribute most to its success.

Cases

Various cases have been evaluated (see Table 1), and results of these studies are discussed below. All cases are evaluated assuming 400 MWe net power generation, 65% capacity factor, Illinois #6 bituminous coal, 90% CO_2 capture, CO_2 compression to 2,200 psia, transported 50 miles and stored in a saline formation.

Table 1 - Cases Evaluated

Case	Description
1	Selexol Scrubbing (2000 Study)
2	Advanced Selexol Scrubbing (2005 Study)
3	Advanced Selexol Scrubbing with Co-Storage of CO_2/H_2S
4	Advanced Selexol with Oxygen-Selective Ion Transport Membrane (ITM) and Co-Storage
5	Water Gas Shift (WGS) Membrane with Co-Storage
6	Water Gas Shift/Oxygen Membranes with Co-Storage
7	Chemical Looping with Co-Storage

Base Case – This is the case to which other cases are compared and is based on a design (*Case 3B*) presented in a 2000 DOE/EPRI study [1]. The plant design approach is market-based, and the configuration reflects current information and design preferences—use of a single combustion turbine coupled with a heat recovery system that generates steam for use in a single steam turbine generator. The gasifier chosen for this configuration has a cryogenic air separation unit (ASU) in place to supply 95% oxygen to the gasifier. Raw fuel gas exiting the gasifier is cooled and cleaned of particulates before being routed to a series of raw gas coolers. After desulfurization in an amine unit, the fuel gas is reheated and fired in the combustion turbine. Gross power output for this plant is 445 MWe [1].

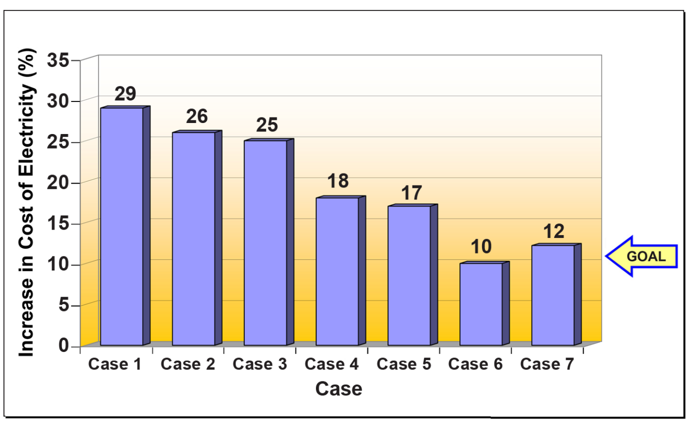

Figure 2. Percent Increase in Cost of Electricity

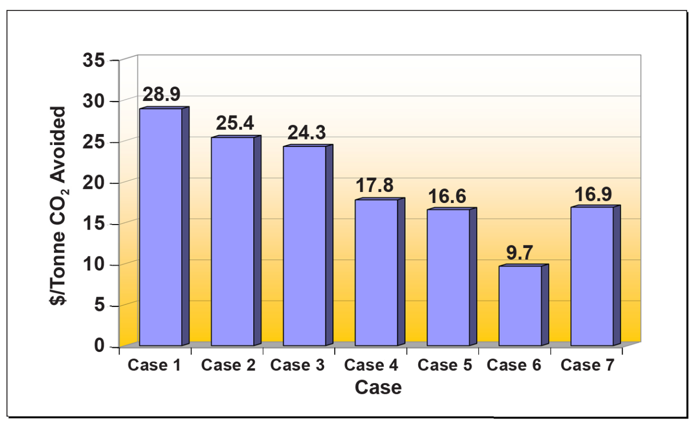

Figure 3. CO_2 Avoidance Cost

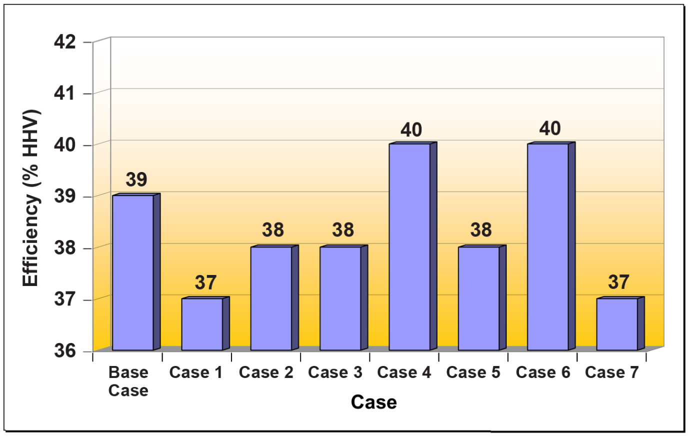

Figure 4. Efficiencies

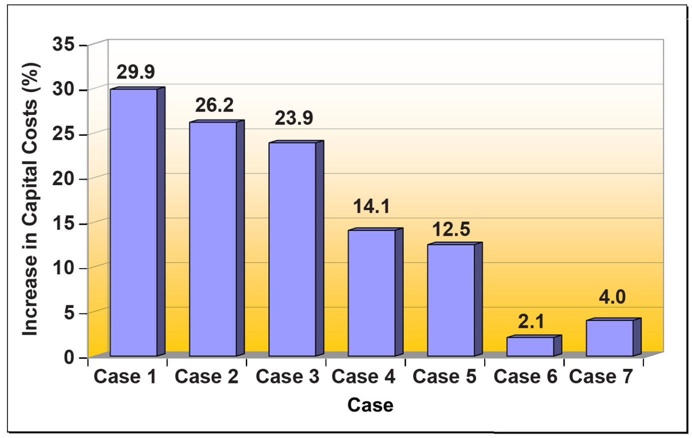

Figure 5. Percent Increase in Capital Costs

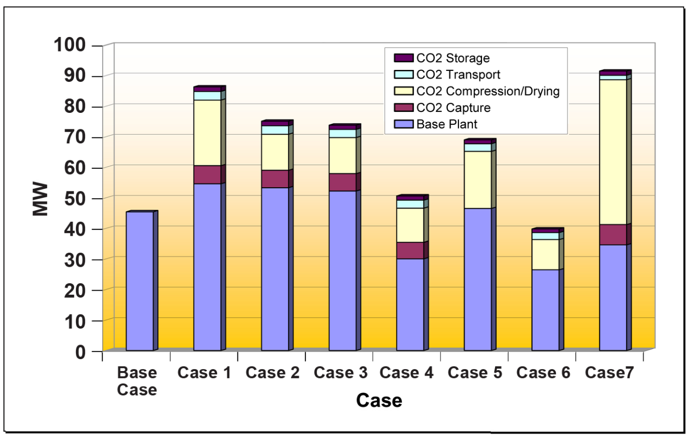

Figure 6. Auxiliary Power Loads

Case 1 – Design basis is the same as the Base Case except that a double-staged Selexol unit is added to capture 90% of the CO_2 in the fuel gas as well as H_2S. Raw fuel gas exiting the gasifier is cooled and cleaned of particulate by a metal candle filter before being routed to a series of water-gas shift reactors (to create a concentrated CO_2 stream by converting CO and H_2O to H_2 and CO_2) and raw gas coolers. Once concentrated, CO_2 is removed in the Selexol unit along with more than 99.7 percent of the H_2S. The captured H_2S is subsequently concentrated and processed in a Claus plant and tail gas treating unit (TGCU) to produce an elemental sulfur product that may be sold. CO_2, exiting the Selexol unit at 25 psia, is dried and compressed to supercritical conditions for pipeline transport. Clean fuel gas from the Selexol unit, now rich in H_2, is fired and expanded in the combustion turbine. Waste heat is recovered from this process and used to generate steam that feeds a steam turbine. Gross power output for this case is 484 MWe [1].

Case 2 – Design is the same as Case 1 except that advanced Selexol replaces traditional Selexol for CO_2 and H_2S capture. This advanced sorbent is assumed to be capable of regenerating CO_2 at a pressure (175 psia) greater than traditional Selexol allows (25 psia). A higher regeneration pressure results in reduced parasitic load from compression. The gross power output for this case is 472 MWe [2].

Case 3 – Design basis is the same as Case 2 except co-sequestration of CO_2 and H_2S is carried out. Based on a 2004 IEA GHG report, "there are no technical barriers with co-sequestration of these components." Thus, this case assumes no Claus plant or tail gas treating unit (TGTU) and no increase in compression and transmission capital costs. Gross power output is 471 MWe [3].

Case 4 – A similar configuration as Case 3 except that an oxygen-selective ion transport membrane replaces a cryogenic ASU as the source of oxygen to the gasifier. A 41% decrease in ASU capital cost and 54% decrease in ASU parasitic loads are assumed. Gross power output for this case is 448 MWe.

Case 5 – Same configuration as Case 1 with two modifications: 1) a hydrogen-selective Water Gas Shift (WGS) membrane reactor replaces traditional WGS reactors for conversion of CO to CO_2, and 2) co-sequestration of CO_2 and H_2S is employed. As syngas passes through the WGS membrane reactor, H_2 passes from the retentate side of the membrane to the permeate side. As such, by LeChatliers Principle, the WGS reaction equilibrium is shifted toward further conversion of CO to CO_2, resulting in a concentrated stream of CO_2 and H_2S. Since co-sequestration is being utilized, sulfur removal equipment (Selexol, Claus, TGTU) is not necessary. Gross power output for this case is 467 MWe.

Case 6 – Same design basis as Case 5 except that an oxygen-selective ion transport membrane replaces a cryogenic ASU as the source of oxygen to the gasifier. Gross power output for this case is 438 MWe.

Case 7 – Chemical looping, through a coupled solid reducer and oxidizer, is used to indirectly provide the oxygen for the gasification of coal and to capture CO_2. The oxidizer is designed to capture oxygen from air utilizing a stream of recirculated solids. The chemistry in the oxidizer is:

$$CaS + 2O_2 \rightarrow CaSO_4 + Heat$$

The reducer then produces a medium-Btu gas by reducing $CaSO_2$ in the presence of coal by the following reactions:

$$4C + CaSO_4 + Heat \rightarrow 4CO + CaS$$
$$8H\ (in\ Coal) + CaSO_4 + Heat \rightarrow CaS + 4H_2O$$
$$H_2O + C + Heat \rightarrow H_2 + CO$$

A second process occurring in the reducer is the water-gas shift reaction:

$$CO + H_2O \rightarrow H_2 + CO_2$$

Finally, the CO_2 is captured in the reducer according to the following reaction:

$$CaO + CO_2 \rightarrow CaCO_3 + Heat$$

The medium-Btu fuel gas and entrained solids stream leaving the reducer enter a particulate removal device, where the solids, now rich in $CaCO_3$, are separated from the gas. A calciner regenerates CaO and CO_2 from the $CaCO_3$. The cleaned fuel gas, which is mostly hydrogen, serves as the feed stream to the Power Generation System. Power production is provided by a single train gas turbine with a heat recovery steam generator and an 1,800 psig/1,000 ºF /1,000 ºF steam cycle. Gross power output for this case is 492 MWe [4].

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1. *Evaluation of Innovative Fossil Fuel Power Plants with CO_2 Removal*, EPRI, Palo Alto, CA, U.S. Department of Energy – Office of Fossil Energy, Germantown, MD, and U.S. Department of Energy/NETL, Pittsburgh, PA: 2000.1000316.

2. *Simteche Hydrate CO_2 Capture Process—Engineering Analysis,* DOE/NEXANT, Draft Report, October, 2005.

3. *Impact of Impurities on CO_2 Capture, Transport and Storage*, IEA Greenhouse Gas R&D Programme, Report Number PH 4/32, August 2004.

4. *Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers*, Alstom Power, Inc., May, 2003.

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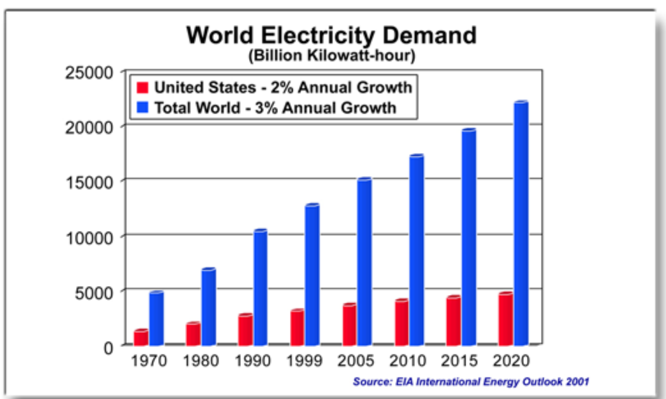
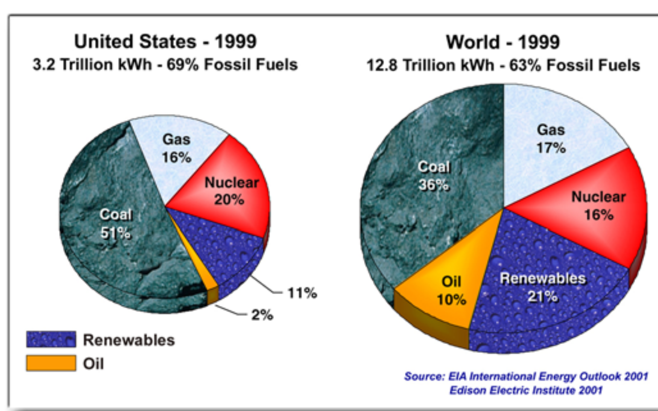
Coal Technologies Offer CO_2 Capture Benefits

With potential implications surrounding global climate change and carbon dioxide (CO_2), technology and policy options are being investigated for mitigating carbon dioxide emissions. Electric power generation represents one of the largest CO_2 contributors in the United States. Electricity consumption is expected to grow and fossil fuels will continue to be the dominant fuel source. Therefore, fossil fuel based power generation can be expected to provide an even greater CO_2 contribution into the future. Coal fuels more than half of this electric power generation capacity and typically produces the cheapest electricity among all fuel sources. Compared to other fossil fuels, coal suffers inherent CO_2 disadvantages relative to its combustion characteristics and the fact that most coal power plants are old and inefficient. These CO_2 disadvantages present a major challenge to coal-based power generation. Fortunately for coal, off-the-shelf CO_2 capture technologies provide performance and cost benefits for minimizing carbon dioxide emissions relative to other fossil fuel sources.

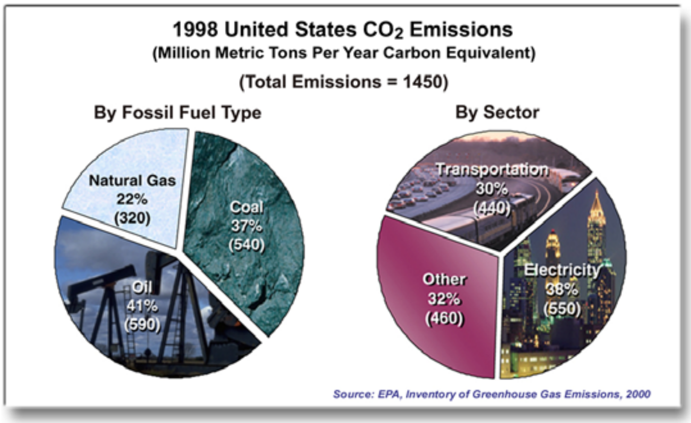
Electricity Use is Growing



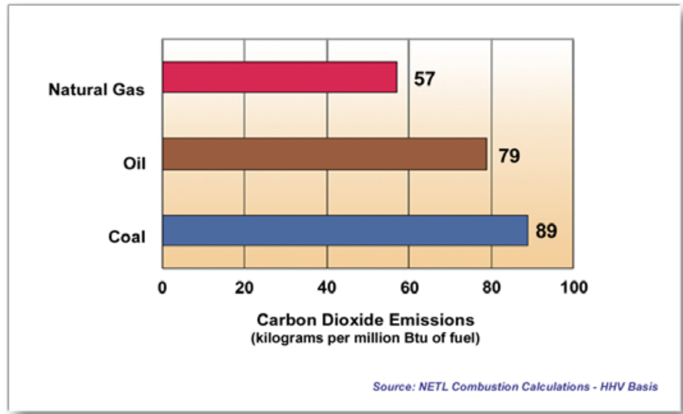
Fossil Fuels: Dominant Energy Source for Electricity



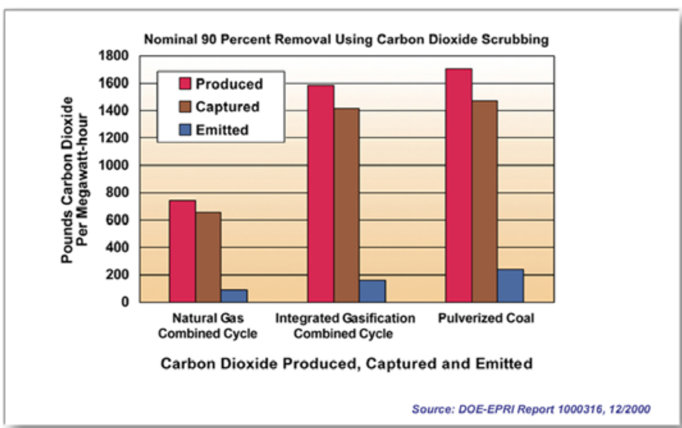
Coal Technologies Offer CO_2 Capture Benefits



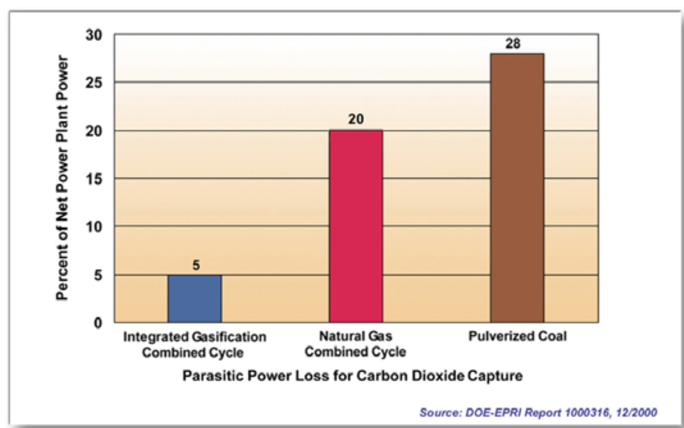
Coal & Electricity Are Major CO_2 Contributors



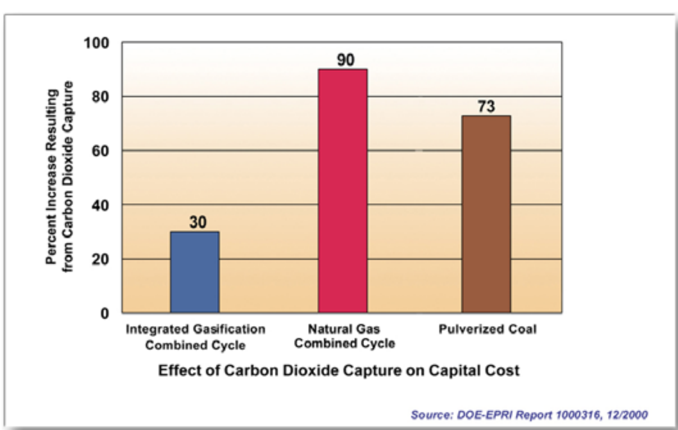
Fossil Fuel CO_2 Emissions



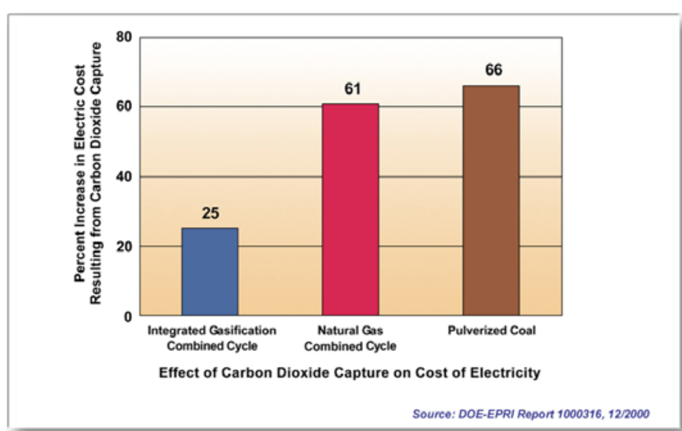
Substantial CO_2 Capture From Coal Power Plants



IGCC Minimizes Energy Penalty of CO_2 Capture



Coal Technologies Minimize Impact on Capital Cost



IGCC Minimizes Impact on Cost of Electricity

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NATIONAL ENERGY TECHNOLOGY LABORATORY

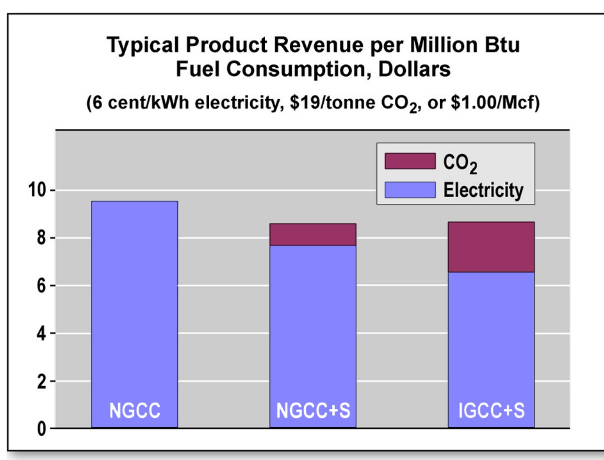
COAL-BASED IGCC OFFERS CO_2 CAPTURE BENEFITS FOR OIL RECOVERY

Background

As the demand for electricity steadily increases and concerns grow about greenhouse gas emissions, scientists are focusing on a coal-based technology that holds promise for addressing these issues. The technology, Integrated Gasification Combined Cycle equipped with a carbon capture and sequestration system (IGCC+S), can produce electricity at a competitive price, clean the environment of the most important greenhouse gas — carbon dioxide (CO_2) — and use the CO_2 as a valuable by-product to recover additional oil from mature reservoirs.

Scientists compared IGCC+S with two other approaches to determine how each would fare in a U.S. market that assumes an increased use of CO_2 to squeeze more oil out of mature reservoirs in a process called Enhanced Oil Recovery (EOR). The two other approaches were Natural Gas Combined Cycle (NGCC) and NGCC equipped with CO_2-capture technologies (NGCC+S). IGCC+S and NGCC+S, now in various phases of research and development, should be ready for commercialization within the decade. Selling the captured CO_2 for use in EOR projects could help offset the costs of these technologies while producing afford-able electricity and cleaning the environment.

At current and expected prices for natural gas, NGCC is the least expensive generating technology available. Economic projections show that it will provide the majority of additional generating capacity required by the United States over the next several decades. The present study was undertaken to determine if IGCC+S could be cost-competitive with NGCC if the captured CO_2 were marketable for use in EOR. This IGCC+S technology captures 90 percent of generated CO_2, which means that the net emission of CO_2 would only be about one-fifth as large per kilowatt-hour as emissions from NGCC.



Typical Product Revenue per Million Btu Fuel Consumption, Dollars
(6 cent/kWh electricity, \$19/tonne CO_2, or \$1.00/Mcf)

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Coal-Based IGCC Offers CO_2 Capture Benefits for Oil Recovery

Description

Scientists from the U.S. Department of Energy's (DOE) National Energy Technology Laboratory and the Pacific Northwest National Laboratory compared the economics of the three fossil-fuel technologies. They conducted the study to determine the price of electricity and the rate of return on invested capital expected for each of the three fossil-fuel systems. They further assumed that the systems would be built by 2010 and would operate for 20 years. Assumptions on fuel price, thermal efficiency, costs of coal and natural gas, and selling price of electricity and CO_2 were taken into account. The comparison resulted in the following conclusions.

NGCC's CO_2 emissions are less than half of those produced by an IGCC without carbon capture. But, an IGCC+S produces only one-fifth the carbon emissions of the most efficient NGCC. If reducing CO_2 emissions becomes important, an IGCC+S represents a significant improvement over NGCC.

NGCCs equipped to achieve 90 percent carbon capture are not as efficient as an IGCC+S, and the capital cost for providing capture is greater for NGCC than for IGCC. The cost difference is attributed to differences in the capture methods employed in the two generation approaches: from the flue gas in a NGCC and from a synthesis gas in an IGCC. The study indicates that the price of electricity generated by NGCC+S would be higher than that generated by either NGCC (without capture) or IGCC+S.

A large factor in the comparative costs of coal- and gas-based generation systems is fuel price. Compared with the price of oil and natural gas, the price of coal is expected to be stable. In fact, coal prices are expected to decline in the next two decades while the price of natural gas is projected to more than double for the same period. Price projections prepared by DOE's Energy Information Administration were used in the study. A large variability in the price of oil is also projected. In the study, the value of CO_2 for practice of EOR was estimated from published predictions of oil prices by using an historic linkage of prices for the two commodities.

Benefits

When they completed their study, the scientists concluded that IGCC+S could produce electricity profitably in a competitive market with no government subsidy for avoided carbon emissions, as is sometimes invoked as a means of bringing low carbon-emitting technology into the market. The profitability of NGCC is expected to be greater than that of IGCC+S, but uncertainty associated with the return on investment is greater for NGCC than for IGCC+S because of uncertainty of natural gas prices in the future. And finally, the potential for oil recovery is significant. When CO_2 is used for EOR, it can yield an additional 7 to 15 percent of the original oil in a reservoir and extend the life of the field by 15 to 30 years.

CO_2-EOR: The U.S. Landscape

- 66 Projects: > 190,000 bbl/day enhanced production
- 5 CO_2 Domes: > 1300 MMcfd, 30 TCF recoverable reserves (50+ years worth)
- Other CO_2 Sources
- CO_2 Pipeline Infrastructure

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SEQUESTRATION OF CARBON DIOXIDE EMISSIONS IN GEOLOGIC FORMATIONS

Sequestration of Carbon Dioxide Emissions in Geologic Formations

This project is based on the fact that geologic formations, such as oil fields, coalbeds, and saline aquifers, are likely to provide the first large-scale opportunity to sequester concentrated CO_2 emissions. Researchers are trying to determine what effective, safe, and cost-competitive options are available for geologic storage of CO_2 emissions generated from coal, oil, and gas power plants. The research targets formations within 500 km of each power plant in the U.S. The U.S. goal is to reduce the cost of carbon sequestration to $10 or less per net ton of carbon by 2015.

Geologic Sequestration of CO_2 in Deep, Unminable Coalbeds: An Integrated Research and Commercial-Scale Field Demonstration Project

Advanced Resources International, B-P Amoco and Shell Oil are using existing recovery technology to evaluate the viability of storing CO_2 in deep unminable coal seams in the San Juan Basin in northwest New Mexico and southwestern Colorado. The knowledge gained will be used to verify and validate gas storage mechanisms in coal reservoirs, and to develop a screening model to assess CO_2 sequestration potential.

Maximizing Storage Rate and Capacity, and Insuring the Environmental Integrity of Carbon Dioxide Sequestration in Geological Formations

Texas Tech University and its research partners are using nuclear-magnetic resonance well-logging techniques to identify suitable geologic formations for CO_2 storage. Understanding hydraulic fracturing will enable researchers to predict of the behavior of gas in targeted formations to minimize the number of injection wells, while increasing the injected gas volume.

PROJECTS

Geologic Sequestration of CO_2 in Deep, Unminable Coalbeds: An Integrated Research and Commercial-Scale Field Demonstration Project

Principal Investigator:
Scott Reeves, 713-780-0815

Partners: Advanced Resources International, Houston, Texas; B-P Amoco, Houston, Texas; Shell-CO_2 , Houston, Texas

Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide Sequestration in Geological Formations

Principal Investigator:
Alan Graham, 806-742-3553

Partners: Texas Tech University, Lubbock, Texas; Terra Tek, Salt Lake City, Utah; Sandia National Laboratory, Albuquerque, New Mexico; University of New Mexico, Albuquerque, New Mexico

Reactive, Multiphase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau

Principal Investigator:
Richard Allis, 801-581-7849

Partners: University of Utah, Energy and Geoscience Institute, Salt Lake City, UT; Industrial Research Limited (IRL), New Zealand

Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying the Potential of the Black Warrior Coalbed Methane Fairway, Alabama

Principal Investigator:
Jack Pashin, 205-349-2892

Partners: Geological Survey of Alabama, Tuscaloosa, AL; Alabama Power Company, Birmingham, Alabama; Jim Walter Resources, Brookwood, Alabama; University of Alabama, Birmingham, Alabama

Reactive, Multiphase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau

The University of Utah is leading an effort to conduct an in-depth study of deep saline reservoirs in the Colorado Plateau and Rocky Mountain region. The study will enable researchers to determine how much CO_2 can be stored, what happens to the stored gas, and the long-term environmental risks associated with the storage.

Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying the Potential of the Black Warrior Coalbed Methane Fairway, Alabama

The Geological Survey of Alabama and its partners are conducting research to determine the amount of CO_2 that can be stored in the Black Warrior coalbed methane region of Alabama. The effort is focused on developing a broad-based geologic screening model, quantifying CO_2 storage potential of the Black Warrior coalbed methane region, and applying the model to identify additional sites.

Experimental Evaluation of Chemical Sequestration of Carbon Dioxide in Deep Aquifer Media

This project involves Battelle Laboratories evaluating and examining factors that affect the geological and geochemical storage of CO_2 in deep saline formations in the Midwestern U.S. Research presently indicates that the most promising long-term option for sequestration is to dispose of CO_2 in a dense, supercritical phase in deep saline sandstone formations.

Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers in the United States

The University of Texas at Austin's Bureau of Economic Geology is developing criteria for characterizing optimal conditions and characteristics of saline aquifers that can be used for long-term storage of CO_2. A regional U.S. data inventory of saline water-bearing formations is also being developed.

Sequestering Carbon Dioxide in Coalbeds

Oklahoma State University is leading an effort to develop, test, and investigate the ability of injected carbon dioxide to enhance coalbed methane production. The research will investigate competitive adsorption behavior of methane, CO_2, and nitrogen on the surface of a variety of coals to determine how much CO_2 is needed to displace the methane.

The GEO-SEQ Project

Lawrence Berkeley, Lawrence Livermore, and Oak Ridge National Laboratories and their partners are investigating safe and cost-effective methods for geologic sequestration of CO_2. Targeted tasks address the following: (1) Siting, selection, and longevity of the optimal sequestration sites; (2) lowering the cost of geologic storage; and (3) Identification and demonstration of cost-effective and innovative monitoring technologies to track migration of CO_2.

Geologic Sequestration of CO_2

Sandia National Laboratory and Los Alamos National Laboratory have partnered with an independent producer, Strata Production Company, to investigate down-hole injection of CO_2 into a depleted oil reservoir. A comprehensive suite of computer simulations, laboratory tests, field measurements, and monitoring efforts will be used to understand, predict, and monitor the geomechanical, geochemical, and hydrogeologic processes involved. The observations will be used to calibrate, modify, and validate the modeling and simulation tools.

Experimental Evaluation of Chemical Sequestration of Carbon Dioxide in Deep Aquifer Media

Principal Investigator:
Neeraj Gupta, 614-424-3820

Participant: Battelle Columbus Laboratories, Columbus, Ohio

Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers in the United States

Principal Investigator:
Susan Hovorka, 512-471-1534

Participant: University of Texas at Austin, Bureau of Economic Geology, Austin, TX

Sequestering Carbon Dioxide in Coalbeds

Principal Investigators:
K. Gasem and R. Robinson, 405-744-9498

Partners: Oklahoma State University, Stillwater, Oklahoma; Pennsylvania State University, Department of Energy and Geo-Environmental Engineering, State College, PA

The GEO-SEQ Project

Principal Investigator:
Sally Benson, 510-486-7071/7714

Partners: Lawrence Berkeley National Laboratory, Berkley, California; Lawrence Livermore National Laboratory, Livermore, California; Oak Ridge National Laboratory, Oak Ridge, Tennessee; Stanford University, USGS, Texas Bureau of Economic Geology, Alberta Research Council, Chevron, Texaco, Pan Canadian Resources, Shell CO_2, BP-Amoco, and Statoil, Norway

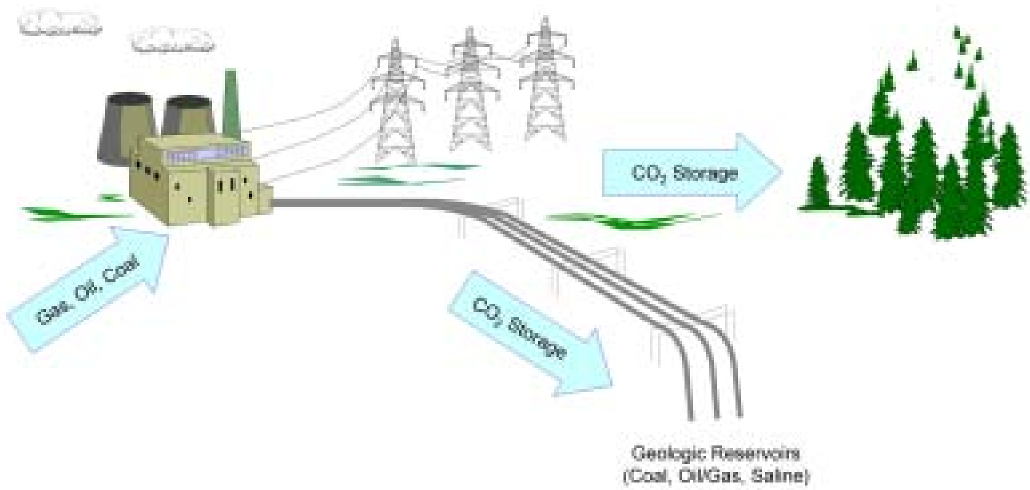
Geologic Sequestration of CO_2

Principal Investigator:
Henry Westrich, 505-844-9092

Partners: Sandia National Laboratory, Los Alamos National Laboratory, Strata Production Company

Sequestration of Carbon Dioxide Emissions in Geologic Formations

CO_2 Capture and Storage



Range of Estimates for CO_2 Sequestration in U.S. Geologic Formations

Geologic Formation	Capacity Estimate (GtC)	Source
Deep saline reservoirs	1-130	Bergman and Winter 1995
Natural gas reservoirs in the United States	25[a] 10[b]	R.C. Burruss 1977
Active gas fields in the United States	0.3 / year[c]	Baes et al. 1980
Enhanced coal-bed methane production in the United States	10	Stevens, Kuuskraa, and Spector 1998

a. Assuming all gas capacity in the United States is used for sequestration
b. Assuming cumulative production of natural gas is replaced by CO_2
c. Assuming that produced natural gas is replaced by CO_2 at the original reservoir pressure

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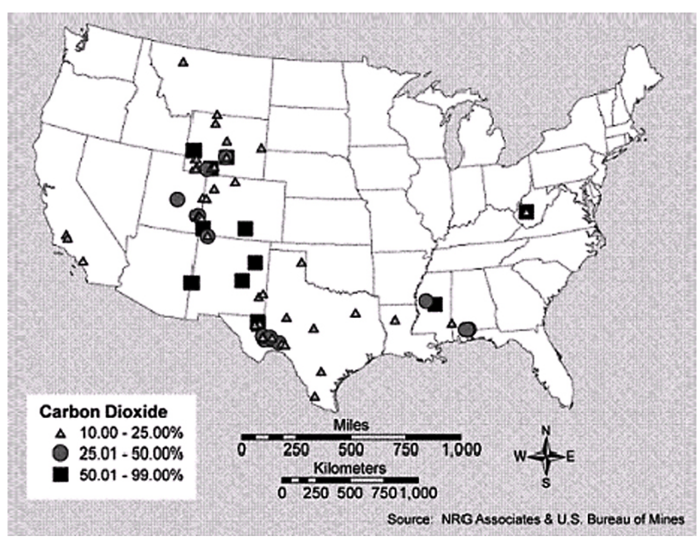
Sequestration

03/2005

Risk Assessment for Long-term Storage of CO_2 in Geologic Formations

The aim of geologic sequestration is to identify and properly utilize formations that will store CO_2 securely — in much the same way as underground formations have stored oil and natural gas for hundreds of millions of years. Yet CO_2 in an underground formation is buoyant and exhibits low viscosity. If unconstrained, it will flow upwards through rock pores and channels until it reaches the atmosphere. Thus there is a fundamental risk of CO_2 escape, particularly low seepage of CO_2 from a storage reservoir. Although highly improbable, large releases of CO_2 are theoretically possible and risk assessment approaches must address this remote possibility. Large scale releases that escape via a fast pathway may damage trees and other plants via elevated concentrations of CO_2 in soil, present asphyxiation hazards through pooling of CO_2 in low-lying areas and confined spaces, and possibly be harmful to drinking water supplies. Risk assessment must be designed to account for all of these possibilities.

The United States Department of Energy's Office of Fossil Energy has developed a clear vision for the safe and environmentally sound operation and management of geologic CO_2 storage facilities over the long term. This vision is rooted in a science-based technology development effort aimed at fully understanding and effectively managing the risks associated with CO_2 storage. The Department's Sequestration Program has a risk assessment R&D component called "Monitoring, Mitigation, and Verification (MM&V). MM&V is defined as the capability to measure the amount of CO_2 stored at a specific sequestration site, monitor the site for leaks or other deterioration of storage integrity over time, and to verify that the CO_2 is stored in a



Scientists are studying natural underground deposits of CO_2 to better understand factors affecting storage permanence. The map above shows the locations of geologic formations in the United States that have contained natural deposits of CO_2 for millions of years.

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The aim of geologic sequestration is to identify and properly utilize formations that will store CO_2 securely.

way that is permanent and not harmful to the host ecosystem. Mitigation capability will provide a response to CO_2 leakage or ecological damage in the unlikely event that it should occur. It is likely that all large scale sequestration deployments will have a mitigation plan in place before operations begin.

MM&V standards and protocols are being developed to ensure permanence, to ensure that the risk of any leakage is minimal, and should it occur, leakage can be safely mitigated. MM&V can be broken into three broad categories: Subsurface, Soils, and Above-ground. Subsurface MM&V involves tracking the fate of the CO_2 within the geologic formations underlying the earth and possible migration to the surface. This area also encompasses developments to mitigate leakage, should it occur. Soils MM&V involves tracking carbon uptake and storage in the first several feet of topsoil and tracking potential leakage pathways into the atmosphere from the underlying geologic formation. This area is especially challenging due to the difficulty in detecting small changes in concentration above the background emissions (~370 ppm) that already exist in the atmosphere. Aboveground MM&V is specific to terrestrial sequestration and involves quantification of the above-ground carbon stored in vegetation. The Sequestration Program is developing instrumentation, detailed computer models and protocols for each of these areas.

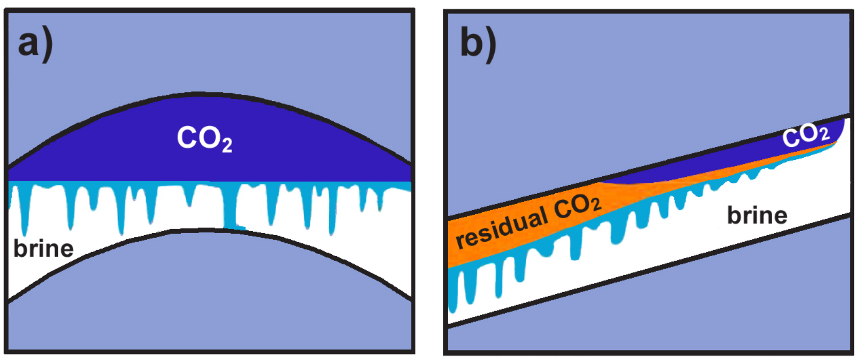
Risk management efforts are being developed to encompass the life of a CO_2 storage project as described below:

> ***Pre-injection.*** A clear picture of the target formation prior to injection (i.e, a baseline) is developed using core samples, fluid samples, and seismic evaluations. Optimal strategies for CO_2 injection are identified, and the flow of injected CO_2 is modeled over long time frames. As a part of the pre-injection assessment, developers consider different CO_2 leakage scenarios. Categories of leakage events include: (1) cap rock or seal failure through capillary failure, faults, or fractures; (2) CO_2 bypass of the cap rock via spillage or migration outside of the target reservoir; and (3) wellbore failure. Particularly in depleting gas or oil formations where many wells have been drilled and abandoned, wellbore failure may represent the highest CO_2 leakage risk. Both the amount of CO_2 leakage and the path that it travels are assessed. In preferred storage formations, a significant portion of any CO_2 leakage becomes trapped in overlying formations. The viability of a system will be judged based on the results of this pre-injection evaluation and only projects that promise very low risk of leakage will be pursued.
>
> ***Operation.*** Once CO_2 injection begins, the transport of CO_2 into the formation will be monitored closely using time-lapse seismic, fluid samples from observation wells, and other data. The monitoring results will be used to both detect any CO_2 leaks or unexpected flow patterns and also to ground truth the reservoir models and hone their predictive capability.
>
> ***Closure.*** CO_2 monitoring will be continued after injection is completed until such a time as it is shown that the stored CO_2 is stable. This may be five to ten years after injection has ceased. A combination of reservoir modeling and CO_2 monitoring snapshots will enable verification of long-term CO_2 storage permanence.
>
> ***Post-closure.*** Protocols for long-term monitoring are currently under development. Long term monitoring will likely include a complete set of characterization and monitoring data which will be invaluable to ensure permanent storage of the sequestered CO_2.

Trapping Mechanisms and Mitigation of Leakage

Scientists have studied the behavior of CO_2 in underground formations and are developing methods for proactively minimizing the risk of CO_2 leakage. This work centers on an improved understanding of the mechanisms for CO_2 storage. The following is a list of key mechanisms.

- ***Cap rock trapping.*** A layer of low-porosity rock serves as a barrier to upward migration of CO_2.
- ***Pore trapping.*** Through capillary and surface tension forces, droplets of CO_2 become affixed into a rock pore space.
- ***Dissolution in brine solution.*** CO_2 is soluble in brine. At 1,900 psi and 30,000 ppm total dissolved solids, one gallon of brine holds 0.4 lbs CO_2.
- ***Mineralization.*** Once in solution CO_2 will react, albeit at a slow rate, with dissolved minerals to form solid mineral carbonates.
- ***Adsorption.*** Unmineable coal seams offer a unique storage mechanism as CO_2 molecules are adsorbed onto the surface of the coal. Adsorbed CO_2 exists as a condensed liquid and is immobile as long as the formation pressure is maintained.



An understanding of CO_2 storage mechanisms will enable CO_2 injection field practices that enhance storage permanence. The figure above, taken from Stanford University, Global Climate Energy Project, June 2004, "Technical Report 2003-2004" http://gcep.stanford.edu/pdfs/technical_report_2004.pdf, is a schematic of CO_2 dissolution in two aquifers. The mobile CO_2 gas phase is dark blue, the dissolved aqueous CO_2 is light blue, residual CO_2 is orange, and the brine is not colored. a) CO_2 gas is held under a structural trap. Dissolution of CO_2 into the brine reduces the CO_2 gas phase volume. b) The CO_2 gas phase migrates along the top of a sloping aquifer, and leaves behind a region of residual CO_2 (i.e., CO2 trapped in pore space). In this case both dissolution and residual CO_2 saturation contribute to the decrease of the mobile CO_2 phase.

CO_2 that is trapped in pores, dissolved in brine, and mineralized will remain immobile and permanently sequestered. Research is aimed at developing injection techniques that maximize secure CO_2 storage via the trapping mechanisms described above. If CO_2 leakage occurs, steps can be taken to arrest the flow of CO_2 or mitigate negative effects. Examples include, lowering the pressure within the CO_2 storage formation to reduce the driving force for CO_2 flow and possibly reverse faulting or fracturing; increasing the pressure in the formation into which CO_2 is leaking, forming a pressure plug; intercepting the CO_2 leakage path; and plugging the region where leakage is occurring with low permeability materials. Additionally, research is underway to develop mitigation techniques that involved "controlled mineral carbonation" or "controlled formation of biofilms" that could be used to plug seepage/leakage points in a geologic formation.

Research is underway to develop mitigation techniques that could be used to plug seepage/leakage points in a geologic formation.

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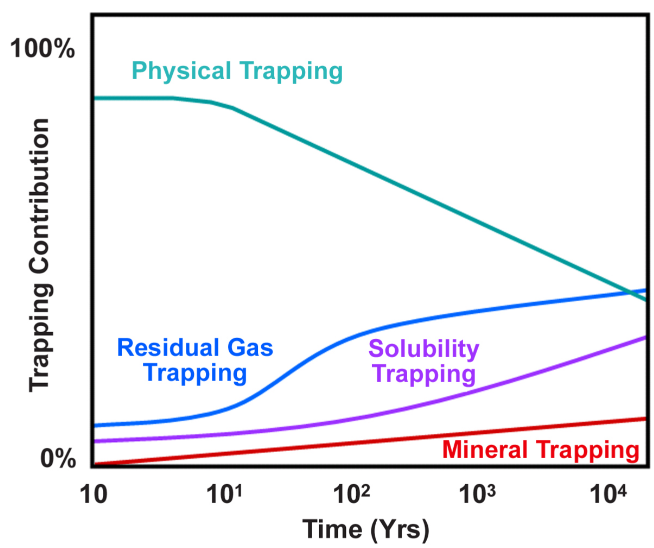
Important for consideration of long term CO_2 storage permanence is the understanding that CO_2 stored in a porous rock formation will tend to become more secure over time (100s of years) as these trapping mechanisms become more predominant, such as CO_2 becomes dissolved into brine or fixed into a mineral carbonate solid. Brine-containing dissolved CO_2 is slightly denser than brine without CO_2 and CO_2-saturated brine will migrate downward in a reservoir, displacing the lighter brine below it. This density effect causes a natural convection that brings the free CO_2 in contact with unsaturated brine. Directionally, mineralization will remove CO_2 from solution and drive further dissolution of CO_2, but the reactions are very slow and less understood.

In summary, the risks of long-term CO_2 storage in geologic formations can be addressed and managed as research provides improved rigorous pre-injection site characterization, close monitoring and accurate modeling of the fate and transport of injected CO_2, field practices to enhance the permanence of CO_2 storage, and capability to reliably detect and mitigate CO_2 leaks in the unlikely even that they occur.



Stable CO_2 stotage mechanisms dominate underground storage over long time frames, providing the promise of secure storage. Source; Sally Benson, 2004, plenary presentation GHGT-7

Program067.pmd

PROGRAM **facts**

U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

05/2005

GEOSEQUESTRATION FIELD EXPERIMENTS

As the concept of carbon sequestration has moved forward, the U.S. DOE has supported field experiments to test the storage of carbon dioxide (CO_2) in underground formations. Acquiring regulatory approval was an important part of these experiments and provides valuable insights for future deployments. Compliance and permitting efforts are highlighted below.

Mountaineer Project, American Electric Power (AEP)

AEP is interested in the possibility of capturing CO_2 from its Mountaineer Power Plant in New Haven, WV and injecting it into a saline formation that underlies the facility. The project is currently in the assessment phase, and no CO_2 has yet been injected. AEP has performed preliminary designs of CO_2 capture and onsite pipeline transport to ensure they do not violate any of the facility's existing permits. Seismic tests of the region have been conducted and a 10,000 foot test well was drilled. These activities were granted a categorical exclusion under NEPA on the basis that they were needed to obtain the data necessary to perform an Environmental Assessment. The West Virginia State Oil and Gas Division granted the well a test well variance (or Class V permit) under the UIC Program . AEP has undertaken a significant community outreach and education effort in preparation for possible future CO_2 injection.

West Pearl Queen, Strata Production

In this experiment, 2,100 tons of CO_2 was injected into a depleted oil reservoir in Lost Hills, NM, 4,000 feet below the surface. The experiment utilized two existing wells, one for CO_2 injection and another for monitoring. The activities received a categorical exclusion under NEPA based on the fact that the test involved a smallscale and unsustained injection deep underground. The experiment was conducted on federal lands and the Bureau of Land Management required the operators to conduct archeological and biological surveys of the area before seismic surveys were allowed. These surveys entailed walking the property to ensure there were no Indian artifacts, endangered species, or sensitive ecosystems that could be compromised by the heavy off-road trucks employed for a seismic survey.

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Frio, University of Texas Bureau of Economic Geology

A small amount of CO2, 3,000 tons, was injected into a deep saline formation. The investigators performed an Environmental Assessment under NEPA and received a Finding of No Significant Impacts (FONSI). As a part of a request of the Texas Commission on Environmental Quality for Class V permit under the UIC program, the project developers prepared a high-quality 100-page document describing the geology and hydrology of the injection zone, plans for construction and operation of the injection well, and results from a reservoir modeling effort. The basis for the Class V request was that the Frio area is primarily a depleted oil field, and that the current experiment was to be conducted in a saline zone for the purposes of using an undisturbed geology that would provide clearer data and enhanced learning. The Class V permit was granted.

Central Appalachian Basin, Consol Energy

This field test is being coordinated with a primary coal bed methane (CBM) recovery project. Roughly 26,000 tons of CO_2 will be injected into a coal seam at the end of primary CBM recovery in late 2005. The well employs slant hole technology and has the potential to be highly effective in enhanced CBM recovery. The operators performed an Environmental Assessment under NEPA and received a Finding of No Significant Impacts (FONSI). The primary CBM recovery project required permits for gas recovery wells and produced water.

Tiffany, Burlington Resources

This experiment had minimal permitting requirements. It was conducted in an established natural gas production area, the San Juan Basin in New Mexico, and utilized existing infrastructure including a pipeline and injection wells. Research was conducted by Advanced Resources International following the 6-year commercial injection of 280,000 tons of CO_2 for CBM recovery.

Weyburn, Alta Energy

This field test is affiliated with the commercial scale EOR operation at Weyburn. The injection wells were permitted as a part of the ongoing oil production operations at the Weyburn field. The major permitting activity required for the field test was for the 140 mile pipeline needed to transport CO_2 from Dakota Gasification to the Weyburn field. The segments on the U.S. and Canadian side were of course under different jurisdictions. After a public hearing, Canada's National Energy Board approved the application from Souris Valley Pipeline in October 1998. In the United States, the pipeline was approved by the Federal Energy Regulatory Commission. On the U.S. side the pipeline travels west from Dakota Gasification and then north following oil reservoirs. This path creates strategic possibilities but also takes the pipeline through North Dakota's cherished bad lands, raising concerns about the pipeline's disturbance of the land. Basin Electric employees and others have worked proactively, in concert with the U.S. Department of Transportation rules, to restore the land disturbed by the buried pipeline. They have focused on reseeding steep slopes. Also, Haines Construction Company, the contractor that built the pipeline, used backhoes instead of conventional trencher, a practice that enabled topsoil to separated and replaced on top. Six years later, in many places, the pipeline route is difficult to discern during aerial surveys.

Taken as a whole, these examples show that sensible project selection and proactive compliance with environmental regulations can provide a clear path for geosequestration as a greenhouse gas mitigation option.

U.S. Regulations Applicable to CO_2 Geologic Sequestration Field Tests

The National Energy Policy Act (NEPA). The goal of NEPA is to ensure the actions of the Federal Government protect the environment. NEPA is a procedural law that compels the Federal government to study the environmental impacts of any action it proposes to take and to communicate the impacts to the public, specifically the public in the vicinity of the proposed action. The process compels the Federal government to look at ways to avoid any adverse environmental impacts and also to explore alternatives to the proposed action in general. NEPA requirements are sequential. A less-stringent Environmental Assessment (EA) is conducted first, and based on the EA a decision is made whether a more stringent Environmental Impact Statement (EIS) is merited. Exploratory wells can receive a categorical exclusion under NEPA.

Underground Injection Control (UIC) Program. The goal of the UIC program is to ensure that drinking water resources are not rendered unfit for use by underground injection of contaminants. UIC considers five classes of underground injection wells. Class I includes hazardous wastes and requires the most stringent assessment and monitoring. This includes a proof of no migration. Class II includes wells to re-inject produced water from oil and and gas production operations and also fluids injected to enhance the recovery of oil and gas. Wells used to inject CO_2 for enhanced oil recovery and enhanced coal bed methane recovery would be categorized as Class II. Class V wells are wells that do not fit into categories I-IV. Class V wells do not require a permit, but an operator must apply for Class V categorization. Small-scale, experimental CO_2 injection wells into saline formations can and have received Class V status.

PROJECT facts

U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Systems, Analyses and Planning

12/2005

CARBON SEQUESTRATION FOR EXISTING POWER PLANTS FEASIBILITY STUDY

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Background

There is growing concern that increased emissions of CO_2 and other greenhouse gases (GHG) to the atmosphere is resulting in climate change with undefined consequences. This has led to a comprehensive program to develop technologies to reduce CO_2 emissions from coal-fired power plants. New technologies, such as advanced combustion systems and gasification technologies hold great promise for economically achieving CO_2 reductions. However, if the United States decides to embark on a CO_2 emissions control program, employing only new, cleaner technologies will not be sufficient. It may also be necessary to reduce emissions from the existing fleet of power plants. This study will build on the results of previous work to help determine better approaches to capturing CO_2 from existing coal-fired power plants.

Description

This study will provide input to potential electric utility actions concerning GHG emissions mitigation, should the U.S. decide to reduce CO_2 emissions. If this is to be done in the most economic manner, it will be necessary to know what level of CO_2 recovery is most economical from the point of view of capital cost, cost of electricity (COE), and operability.

Although switching to natural gas is an option, a tight supply and rising costs may prevent this from being a universal solution. Also, fuel switching may not provide the desired CO_2 emission reductions; and, therefore, some form of CO_2 capture may be required. Captured CO_2 could be sold for enhanced oil or gas recovery or sequestered. The results of this CO_2 capture study will enhance the public's understanding of post combustion control options and influence decisions and actions by government regulators and power plant operators relative to reducing GHG CO_2 emissions from power plants. This study will evaluate the impact on plant output, efficiency, and CO_2 emissions, from the addition of CO_2 capture resulting systems to an existing coal-fired power plant. Cost estimates will be developed for the systems required to capture, purify and compress the CO_2 prior to transport for use or sequestration. Economic evaluation will determine incremental COEs and CO_2 mitigation costs.

In a report titled, "Engineering Feasibility and Economics of CO_2 Capture on an Existing Coal-Fired Power Plant," ALSTOM Power Plant Laboratories (ALSTOM) evaluated the impact of adding facilities to capture 90% of the CO_2 from American Electric Power's (AEP) Conesville Unit No. 5, a subcritical, pulverized-coal (PC) fired unit. The study indicated that removing 90% of the CO_2 from the flue gas using amine scrubbing would increase the COE by 4 to 6 cents per kilowatt hour and decrease net power by 40%. Based on these results, further study was deemed necessary to find a better approach for capturing CO_2 from existing PC fired power plants. This project will extend the previous work by evaluating other cases for the same plant used in the previous study, and the work will be performed at the same level of detail and accuracy.

Timeline

Task	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
Design Basis Development	X	X										
MEA & Gas Compression Process Designs & Regeneration Steam Integration Concept			X	X	X	X	X					
Equipment Selection & Costing					X	X	X	X				
Overall Plant Performance Analysis & CO_2 Emissions								X	X			
Economic Analysis & Comparisons									X	X		
Project Management & Reporting	X	X	X	X	X	X	X	X	X	X	X	X
Final Report											X	X

Objectives

The overall objective of this study is to conduct a comprehensive evaluation of the technical and economic feasibility of retrofitting an existing PC fired electric generation power plant for various levels of CO_2 capture. Specific objectives are to:

- Develop a design basis for the study.
- Extend previous work by evaluating the effect on COE and plant performance of 30%, 50%, 70%, and 90% CO_2 capture (90% capture was evaluated previously with a different amine).
- Obtain a high degree of participation by AEP's Conesville personnel.
- Compare results to new supercritical PC and IGCC power plants with 90% CO_2 recovery.
- Assess improved CO_2 capture with Fluor Daniels Econamine Plus solvent.
- Perform a "value engineering" study of solvent scrubbing for CO_2 capture to evaluate potential areas of cost savings, such as heat integration, alternative materials and equipment types, fewer absorbers and strippers, etc.
- Separate CO_2 capture economics from other costs, such as gas cleanup costs.
- Develop curves showing performance and costs as a function of CO_2 removal percent.
- Evaluate the option of achieving intermediate levels of CO_2 removal by bypassing part of the flue gas around the scrubber and operating at 90% CO_2 capture for the rest of the gas.

- Analyze each case with replacement power using three options: purchase from a new supercritical PC plant with 90% CO_2 capture; purchase from a new natural gas combined cycle (NGCC) plant with 90% CO_2 capture; and purchase from an liquefied natural gas (LNG) combined cycle plant with 90% CO_2 capture.

- Evaluate the impact of the results of this study on the potential for capturing CO_2 from the existing fleet of PC plants in the U.S., based on a comprehensive assessment of existing plants, categorized according to size and life expectancy.

- Estimate the likelihood of successful CO_2 capture for these different groups, and complete several "what-if" scenarios to calculate the range of CO_2 removal potential for different ages of plants.

ALSTOM has teamed with AEP, ABB Lummus Global Inc (ABB), and ALSTOM Steam Turbine Group to perform this study. AEP will serve as the Conesville host site provider (see Figure 1). ABB will design and develop performance and costs estimates for the gas processing systems. Steam Turbine will integrate the steam cycle with the amine system and provide steam turbine performance and modification costs. ALSTOM will develop the study design basis, boiler island modifications and costs, plant economic analysis, and reporting.

Benefits

This study will significantly increase the information available on the impact of retrofitting CO_2 capture to existing PC fired power plants. Such information is critical for deciding on the best path to follow for reduction of CO_2 emissions, should that become necessary. This study will better inform the public as to the issues involved in reducing CO_2 emissions, provide regulators with information to assess the impact of potential regulations, and provide data to plant operators concerning CO_2 capture technologies. This effort will contribute to achieving necessary controls in the most economically feasible manner.

Figure 1 AEP Conesville Plant – Unit No. 5 Steam Generator Indicated

PROJECT DURATION

January 2006 – December 2006

COST

Total Project Value

$473,000

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